Space Charge and CSR Microwave Physics in a Circulated Electron Cooler

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and

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Here CSR stands for "Coherent Synchrotron Radiation" instead of "Cryogenic Storage Ring"

Outline

I. Introduction
   - Requirements of CCR
   - MBI in Early Design of CCR for MEIC

II. CSR and LSC induced Microbunching Instability (MBI)

III. Analysis of MBI for non-magnetized beams

IV. Mitigation Method
   - Lattice choices
   - Magnetized beam

V. Conclusion

I. Introduction

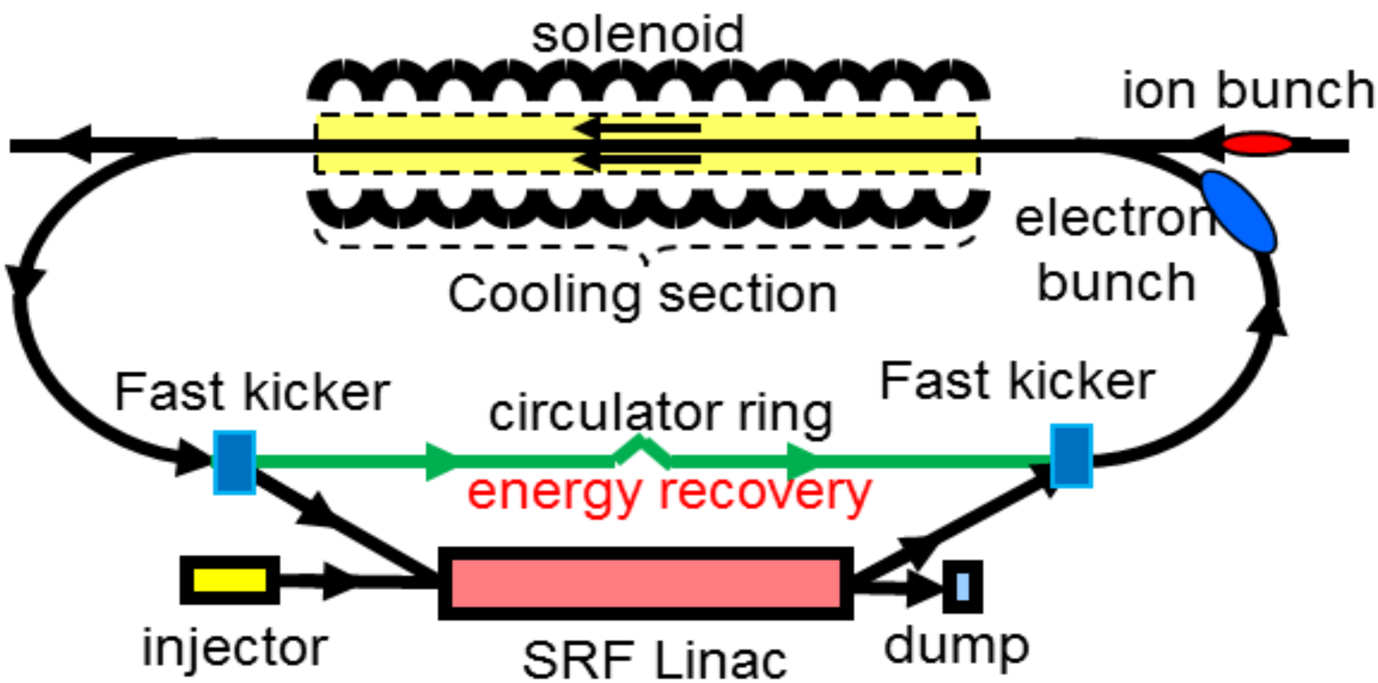
Motivation to study microwave instability (MBI):

- CCR requires the transport of high intensity beams while preserving brightness of phase space quality
- Early design of CCR of MEIC
- First numerical observation of CSR effect on microbunching instability (MBI) in CCR of MEIC

CCR for High Energy Electron Cooling

- Cooling high energy ion beam requires high energy electrons accelerated by RF cavity ----needs bunched beam cooling
- Efficient electron cooling at high energy demands
  - High average current for the cooling beam
  - High beam power
  - High phase space quality of the cooling beam
- ERL allows the beam power recycled by the linac
- CCR is proposed to reduce the demand for high average current from the electron source and in the linac

Illustration of CCR of MEIC

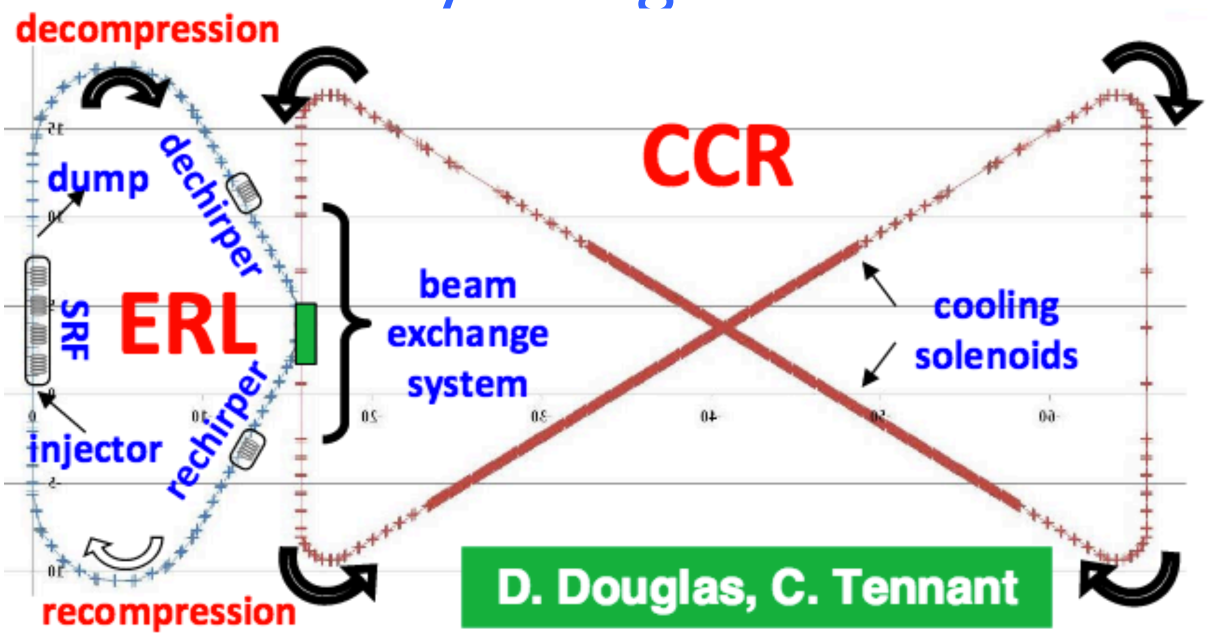


- The electron beam will be reused for cooling the ion beam multiple times by circulating in the CCR for multiple turns

Requirements for ERL-CCR Cooler

- The success of the ERL-CCR design concept is measured by:
  - The maximum number of circulations in the CCR before the bunch self-heating during its transport in the ring
  - Full energy recovery after the circulations
- The cooler performance is determined by:
  - The technology of ultra fast kicker (Amy Sy's talk on Tuesday)
  - The ability to transport high-intensity beam while preserving high beam phase space quality
- Collective interaction of the high-intensity bunch tends to cause instability and presents significant challenge in beam dynamics

Early Design of ERL-CCR for MEIC



(Tennant and Douglas, 2012)

Table 1: Relevant parameters for the CCR.

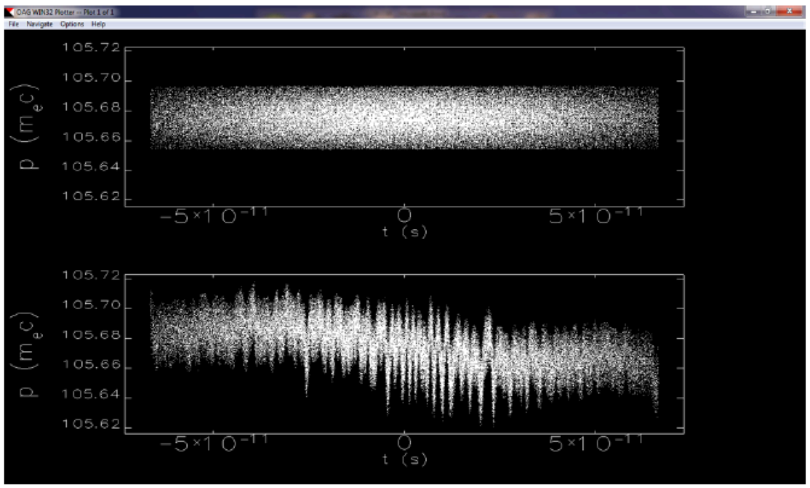
Parameter	Value
Beam energy (MeV)	54
Bunch charge (nC)	2
Repetition rate (MHz)	750
Relative energy spread	10^{-4}
RMS bunch length (ps)	33.33
Longitudinal emittance (keV-psec)	180
Transverse normalized emittance (mm-mrad)	3
Cooling solenoid field (kg)	20

Numerical Observation of Microbunching Instability

Bunch Longitudinal Phase Space Distribution

Elegant tracking results

p



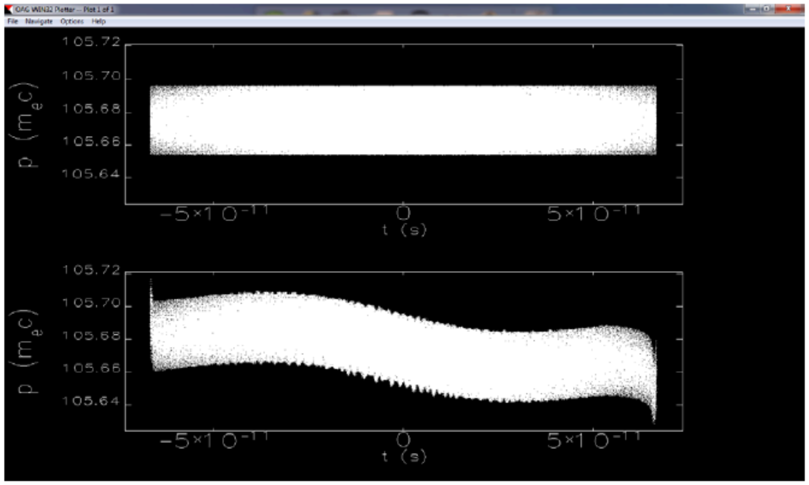
t

100K particles

Single turn

No quiet start

p



t

1000K particles

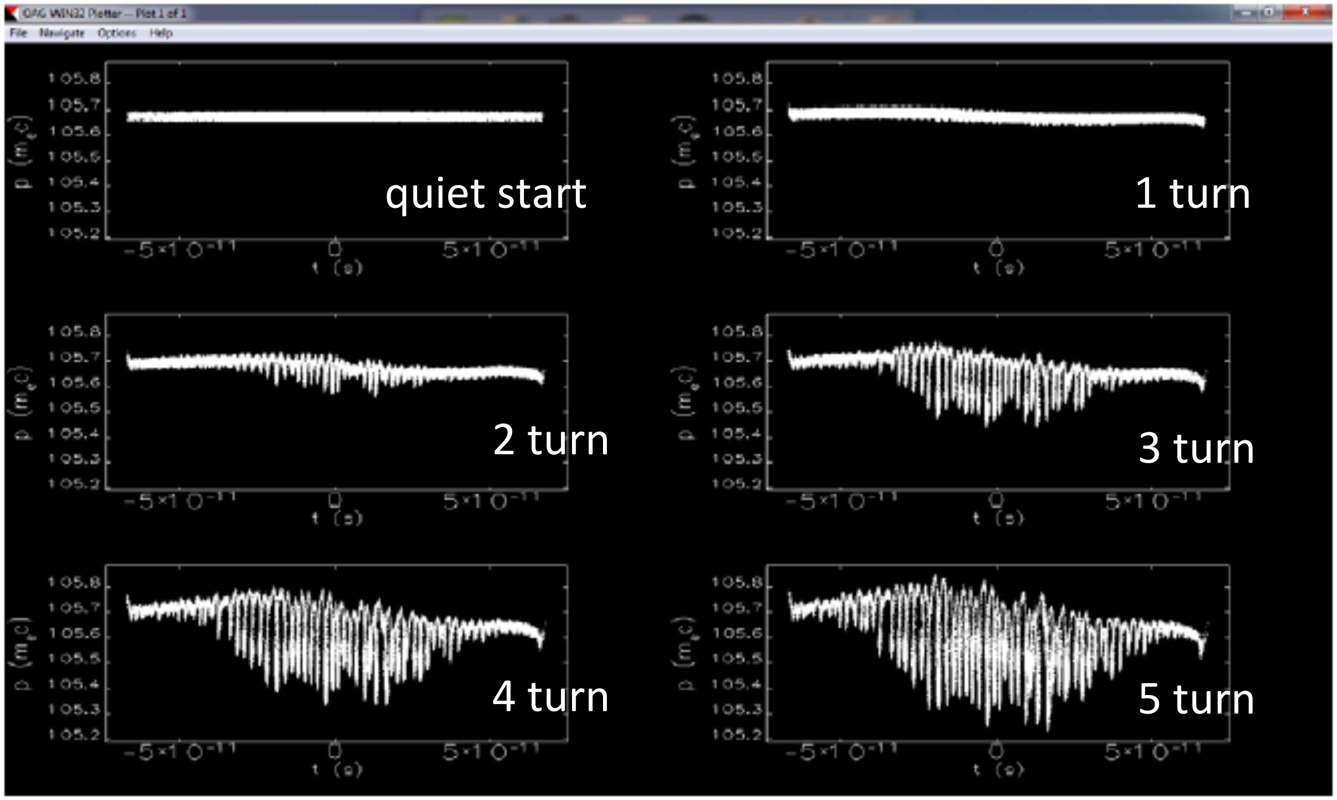
Single turn

With quiet start

(Tennant and Douglas, 2012)

(Nissen *et al.*, 2014)

Evolution of Longitudinal Phase Space



Elegant tracking Results

(100K particles)

Table 2: Evolution of electron bunch parameters as a function of turns in the CCR.

	1 Turn	2 Turns	3 Turns	4 Turns	5 Turns
ε_x (mm-mrad)	2.9	3.1	3.8	4.5	5.1
ε_y (mm-mrad)	2.9	2.9	3.0	3.1	3.2
σ_t (ps)	29.33	29.31	29.28	29.24	29.19
$\sigma_{\Delta E/E}$ (%)	0.012	0.027	0.066	0.096	0.117

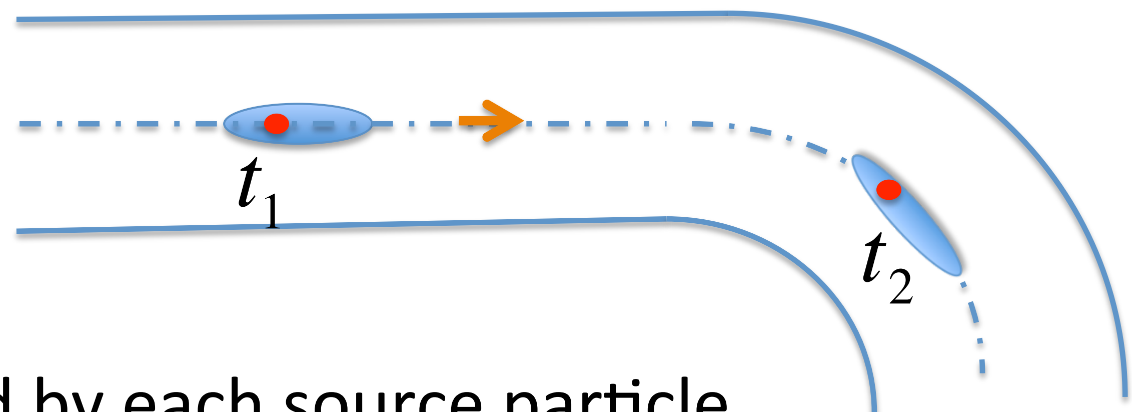
Observation and Questions

- The beam is severely microbunched after a few revolution in the CCR.
- The phase space distribution depends sensitively on
  - initial condition
  - the number of particles used in simulation
- Questions
  - Are these results real or numerical artifacts?
  - How to understand the underlying physics?
  - How to mitigate these microbunching instability

II. LSC and CSR induced Microbunching Instability (MBI)

- LSC on straight path
- CSR interaction in magnetic dipoles
- Physics of Microbunching instabilities
- Challenges of Numerical Simulation

Self-Interaction Among Particles in a Bunch



- EM fields generated by each source particle

$$\vec{E}_0 = e\left(\frac{\vec{n}-\vec{\beta}}{\gamma^2(1-\vec{\beta}\bullet\vec{n})^3 R^2}\right)_{ret} + \frac{e}{c}\left(\frac{\vec{n}\times(\vec{n}-\vec{\beta})\times\dot{\vec{\beta}}}{(1-\vec{\beta}\bullet\vec{n})^3 R^2}\right)_{ret}$$

Coulomb field:
Important on straight path

Synchrotron radiation field:
Important on curved orbit

- Longitudinal wakefield by the bunch on each test particle

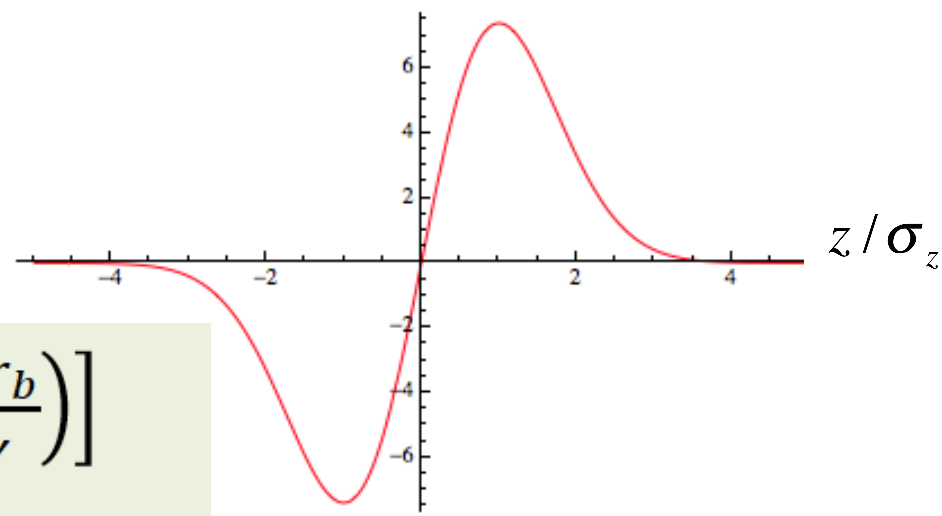
$$\frac{dW}{ds} = -\frac{1}{c}\int\left(e\vec{E}_0(\vec{r},\vec{r}')\bullet\vec{v}\right)\rho(\vec{r}',t')d^3\vec{r}', \quad \left(t' = t - \frac{|\vec{r}-\vec{r}'|}{c}\right)$$

LSC Interaction on Straight Path

- Longitudinal space charge (LSC) wakefield for a Gaussian bunch

$$W_{||}(z) = \frac{N_e r_e (m_e c^2)}{(\gamma\sigma_z)^2} \bullet \text{(form factor)} \propto \frac{I_{peak}}{\gamma^2 \sigma_z}$$

Typical Form factor



- Longitudinal impedance

$$\tilde{W}_{LSC}(k) = Z_{LSC}(k) I(k)$$

$$Z_{LSC}(k) = \frac{iZ_0}{\pi k r_b^2}\left[1 - \frac{k r_b}{\gamma} K_1\left(\frac{k r_b}{\gamma}\right)\right] \approx \begin{cases} \frac{iZ_0}{\pi k r_b^2} & \left(\frac{k r_b}{\gamma} \gg 1\right) \\ \frac{iZ_0 k}{4\pi\gamma^2}\left(1 + 2\ln\frac{\gamma}{k r_b}\right) & \left(\frac{k r_b}{\gamma} \ll 1\right) \end{cases}$$

(wide beam, low energy)

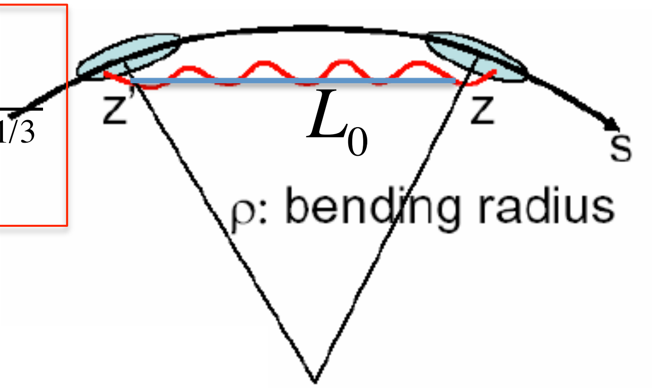
(thin beam, high energy)

LSC "wake" stronger at smaller scale

CSR Interaction on Curved Orbit

- Coherent synchrotron radiation (CSR) wakefield for a Gaussian bunch

$$W_{CSR}(z) = \frac{N_e r_e (m_e c^2)}{\rho^{2/3} \sigma_z^{4/3}} \bullet \text{(form factor)} \propto \frac{I_{peak}}{L_0} \sim \frac{I_{peak}}{\rho^{2/3} \sigma^{1/3}}$$



Overtaking length: $L_0 = (24\sigma_z \rho^2)^{1/3}$

(Ya.S. Derbenev *et al.*, 1995)

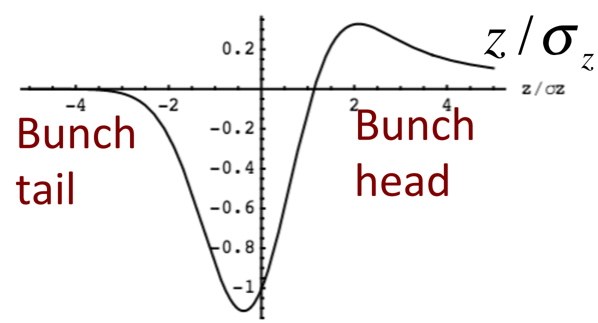
,

- Longitudinal impedance

$$\tilde{W}_{CSR}(k) = Z_{CSR}(k) I(k)$$

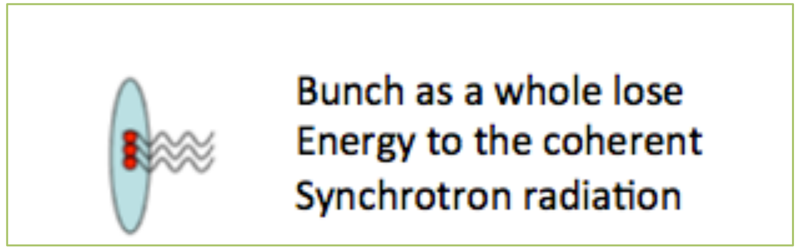
$$Z_{CSR}(k) = -iA \frac{cZ_0}{4\pi} \frac{k^{1/3}}{R^{2/3}} \quad (A = 1.63i - 0.94)$$

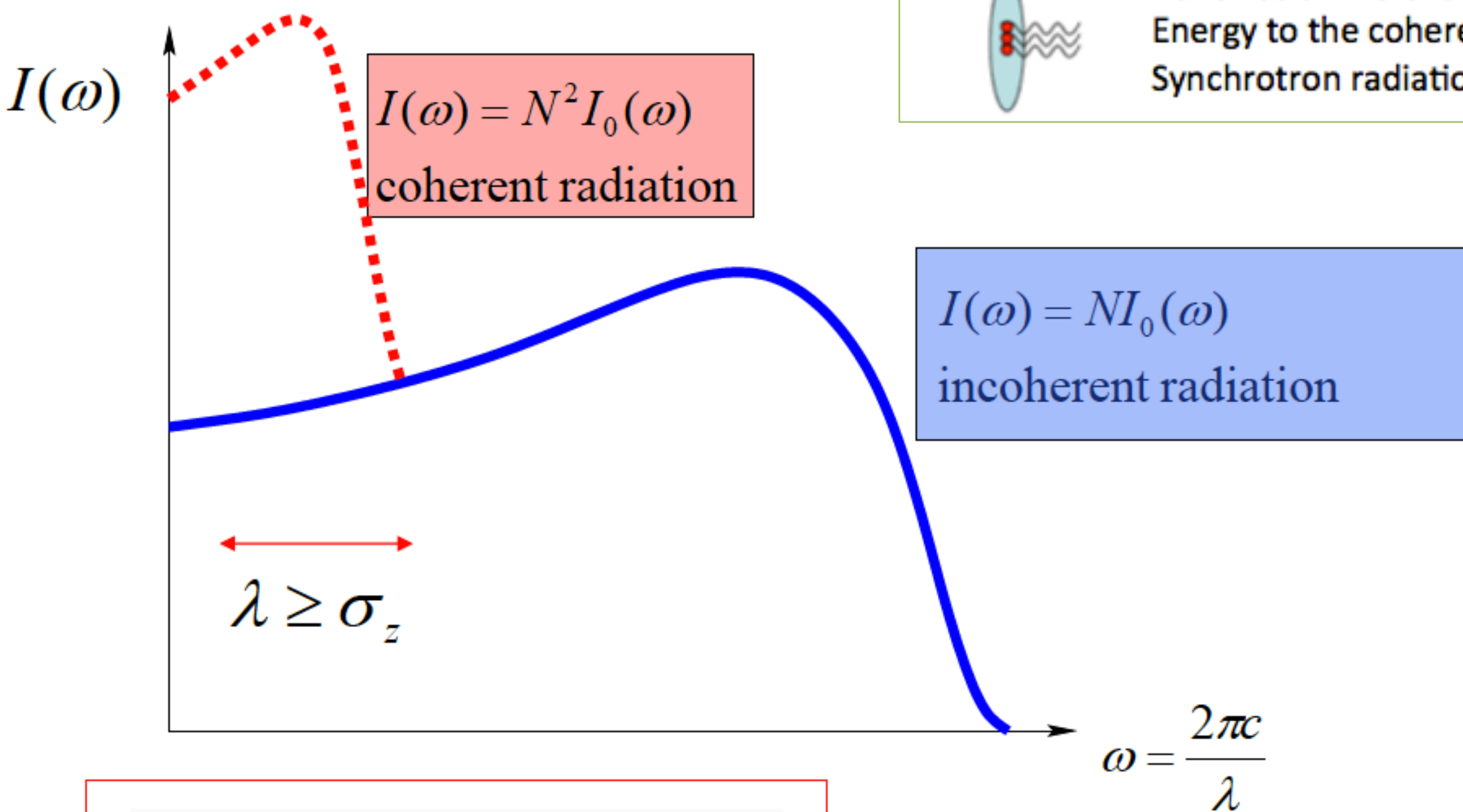
Form Factor



CSR "wake" stronger at smaller scale

Radiation Power Spectrum for N electrons





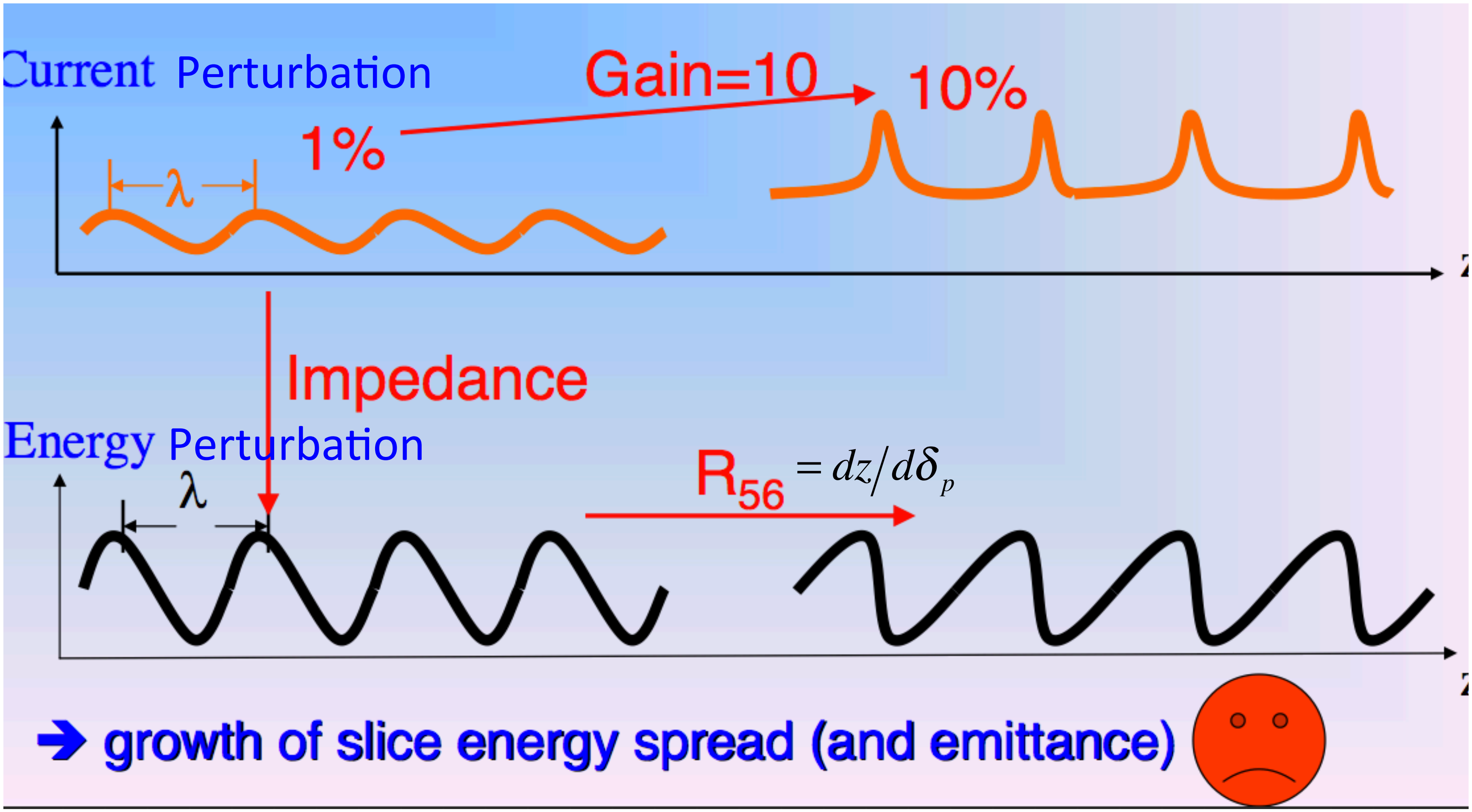
$$\left.\frac{dP}{d\omega}\right|_{\text{bunch}} = \frac{dP}{d\omega} N \left(1 + N|\hat{f}(\omega)|^2\right)$$

Features of LSC and CSR Interaction

- CSR impedance is independent of energy. CSR effect can be important at high energy.

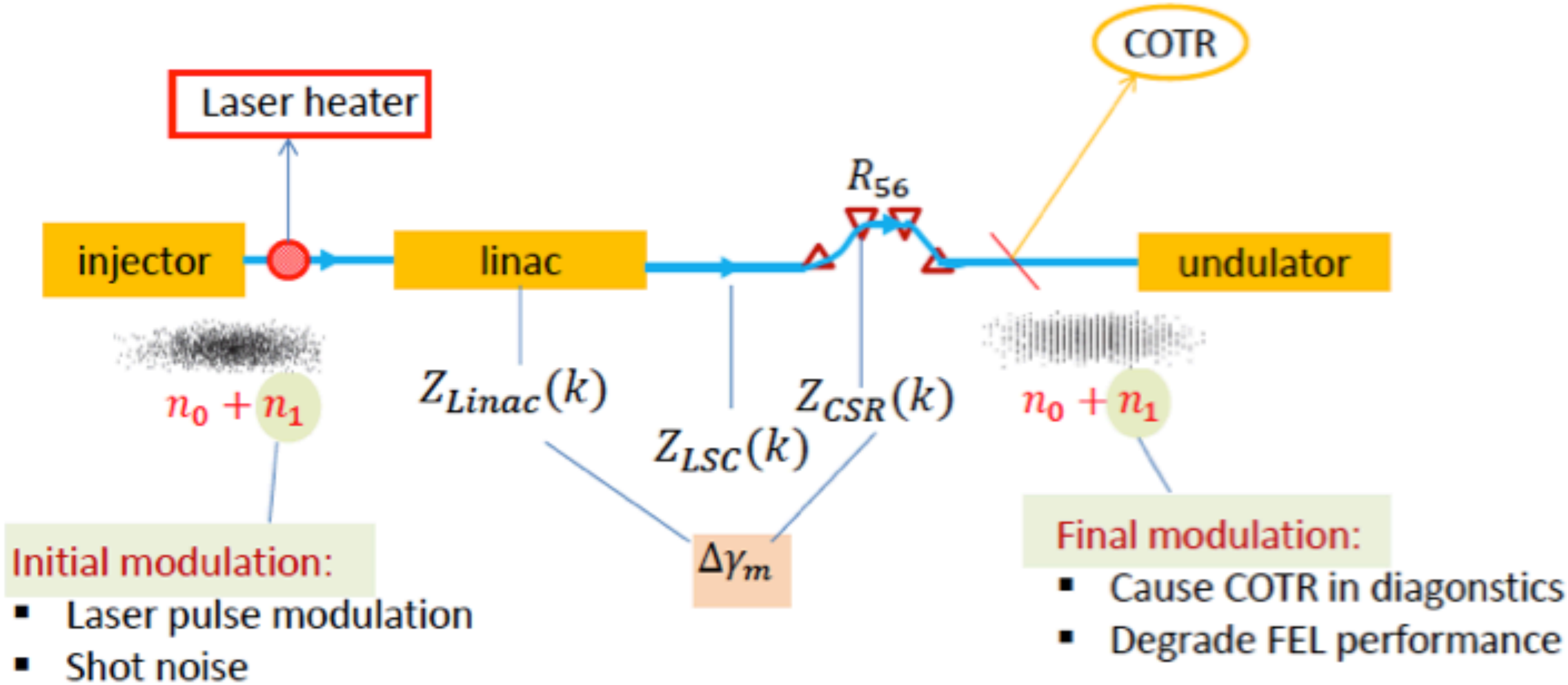
- At high energy, particle longitudinal position in the bunch is frozen, and LSC induced energy modulation keeps accumulation along the beam line. MBI from LSC could be more serious than CSR induced MBI

Microbunching Instability



(Z. Huang, SLAC)

Example: Development of Microbunching Instability in an FEL Driver



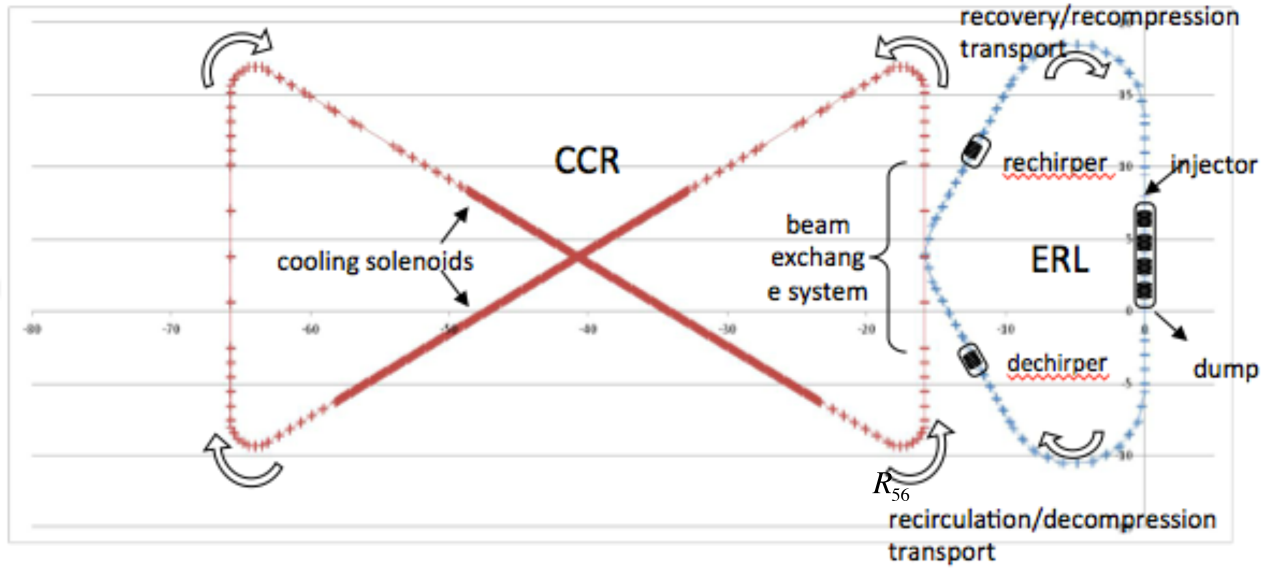
Important factors at play:

- σ_{un}
- Initial modulation
- $\vec{F}^{col}$ or $Z(k)$
- Phase space rearrangement

uBI characterization:

- Bunching factor: $b(k) = < e^{-ikz_i} >$
- Gain : $G(k) = \left|\frac{b_f(k)}{b_0(k)}\right|$
- $\langle |b(k)|^2 \rangle$

Early Design of CCR of MEIC



MBI Process In CCR:

Density Modulation

Z_{CSR} (in dipoles)

Z_{LSC} (on straight)

R_{56} from bends

Energy Modulation

III. Analysis of MBI for Non-magnetized Beams

- Vlasov analysis
  - Linearized perturbative approach
  - Characteristics
- Role of Landau damping by emittance and energy spread
- Dependence on beam current, intrinsic spread and lattice optics
- Comparison with tracking results
  - Convergence
- Impact of lattice design on MBI
- Proposed benchmark with experiment

Microbunching Gain Analysis

- Vlasov equation

$$X = (x, x', y, y', z, \delta)$$

$$\frac{\partial f}{\partial s} + \frac{dX}{ds} \cdot \nabla_X f = 0$$

Linear Approximation:

Small perturbation over a coasting beam

$$f = f_0 + f_1$$

$$f(X;s) = f_0(X_0) - \int_0^s d\tau \frac{\partial f(X_\tau; \tau - 0)}{\partial \delta_\tau} \frac{d\delta}{d\tau}$$

Bunching factor: Amplitude of Fourier component $b(k;s) = \frac{1}{N} \int dX \; e^{-ikz} f(X;s)$

Initial bunching factor: $b_0(k;s) = \frac{1}{N} \int dX_0 \; e^{-ikz} f_0(X_0)$

$$\Rightarrow \quad b[k(s);s] = b_0[k(s);s] + \int_0^s d\tau \, K(\tau, s) b[k(\tau);\tau],$$

Gain Analysis

$$b[k(s);s] = b_0[k(s);s] + \int_0^s d\tau\, K(\tau,s) b[k(\tau);\tau],$$

$$K(\tau,s) = ik(s)R_{56}(\tau \to s)\frac{I(\tau)Z[k(\tau);\tau]}{\gamma I_A} e^{-k_0^2 U^2(s,\tau)\sigma_\delta^2/2}$$

$$\times \exp\left[-\frac{k_0^2 \varepsilon_0 \beta_0}{2}\left(V(s,\tau) - \frac{\alpha_0}{\beta_0} W(s,\tau)\right)^2 - \frac{k_0^2 \varepsilon_0}{2\beta_0} W^2(s,\tau)\right]$$

Longitudinal smearing due to beam intrinsic spread: Landau Damping

(lattice effect)

3. Convert energy modulation at τ to density modulation at s

2. Convert density modulation at τ to energy modulation

1. Density Modulation at τ

- Gain is suppressed by Landau damping at small wavelength, and decrease at large wavelength by impedance. There is an optimal wavelength when the gain peaks

CSR Driven MBI During Bunch Compression

- **Process**

Density modulation

$Z_{CSR}(k)$ ↓ ↑ R_{56}

Energy modulation

- **Assumptions**
  - 4D particle dynamics
  - CSR field based on 1D bunch

- **Approach**
  - Linearized Vlasov equation for 4D phase space
  - Iterative solution

$$b(k(s);s) = b_0(k(s);s) + \int_0^s d\tau K(\tau,s) b(k(\tau);\tau)$$

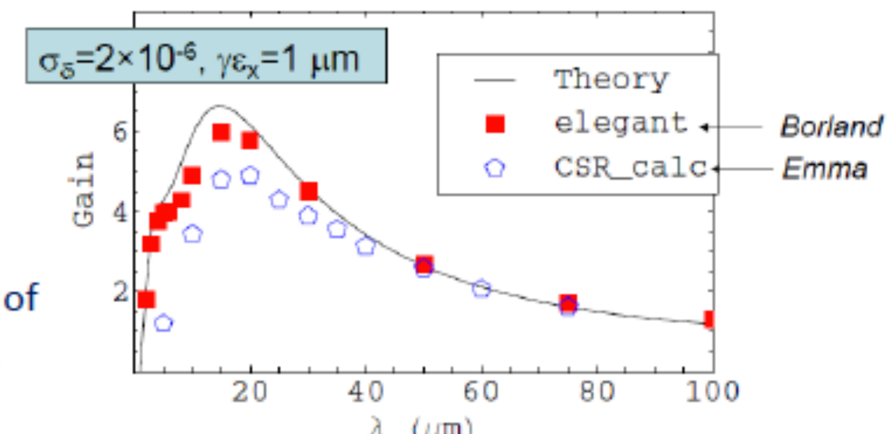
$$\text{kernel } K(\tau,s) = ik(s)R_{56}(\tau \to s)\frac{I(\tau)}{\gamma I_A} Z(k(\tau)) \times \underbrace{\exp(\ldots\varepsilon,\sigma_\delta\ldots)}_{\text{Landau damping}}$$

- **Results**

$$\text{gain}(k) = \frac{b(k(s),s)}{b_0(k(s),s)}$$

(MBI gain in chicane is not large because of emittance caused longigudinal smearing via R_{51} and R_{52})

M. Borland et al., NIM A483 (2002)268



S. Heifets, G. Stupakov and S. Krinsky, PRST-AB 5 (2002) 064401
Z. Huang and K.-J. Kim, PRST-AB 5 (2002)074401

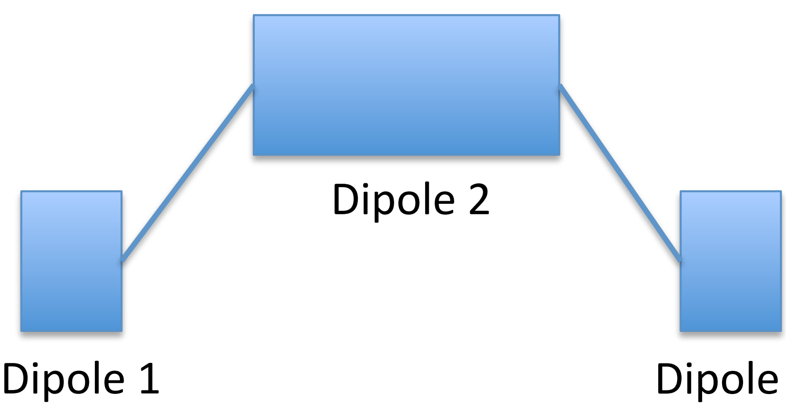
Two-Stage Amplification

(Huang and Kim)

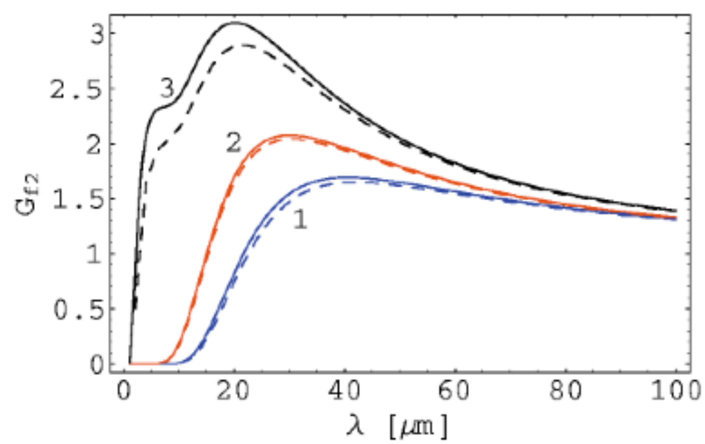
- CSR microbunching

$$b_f(k;s) = b_0(k;s) + \underbrace{\underbrace{\int_0^s ds' K(s',s) b_0(k';s')}_{\text{one-stage amplification}}}_{I_f(1\to 3)+I_f(2\to 3)}$$

$$+ \underbrace{\underbrace{\int_0^s ds' K(s',s) \int_0^{s'} ds'' K(s'',s') b_0(k'';s'')}_{\text{two-stage amplification}}}_{I_f^2(1\to 2\to 3)}$$



LCLS BC2



Space Charge Driven MBI (linac+drift+chicane)

- Process

Density modulation

(in drift + linac) $Z_{LSC}(k)\downarrow$ $\uparrow R_{56}$(in chicane)

Energy modulation

- Assumptions
  - In drift, longitudinal density frozen, space charge oscillation negligible
  - Angular spread do not spoil MBI

- Approach
  - Calculate gain using bunching factor at initial and final path length
  - Mapping from (z_0, δ_0) to (z_f, δ_f), linear expansion using $|k_f R_{56} \delta_m| \ll 1$

- Results

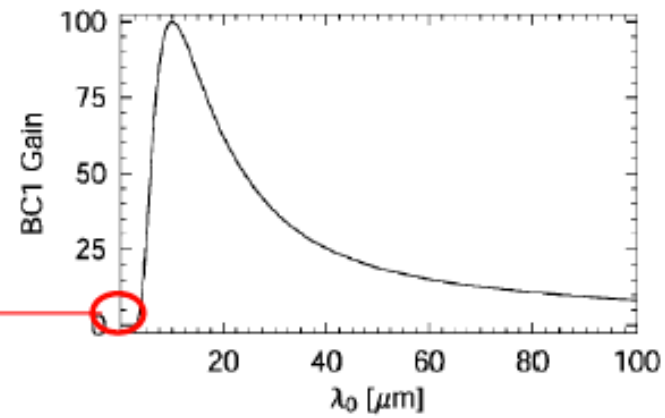
$$\Delta\gamma_m = -\frac{I_0 b_0(k)}{I_A}\int_0^L ds\,\frac{4\pi Z(k_0;s)}{Z_0}$$

$$G \approx \frac{I_0}{\gamma I_A} k_f R_{56} \int_0^L ds\,\frac{4\pi\, Z(k_0;s)}{Z_0} \exp\left(-\frac{1}{2}\left(k_f R_{56}\sigma_\delta\right)^2\right)$$

(assuming initial Gaussian uncorrelated energy distribution)

E. L. Saldin, E. A. Schneidmiller, and M.V. Yurkov, DESY Report No. TESLA-FEL-2003-02, 2003.

Microbunching gain after BC1 of LCLS

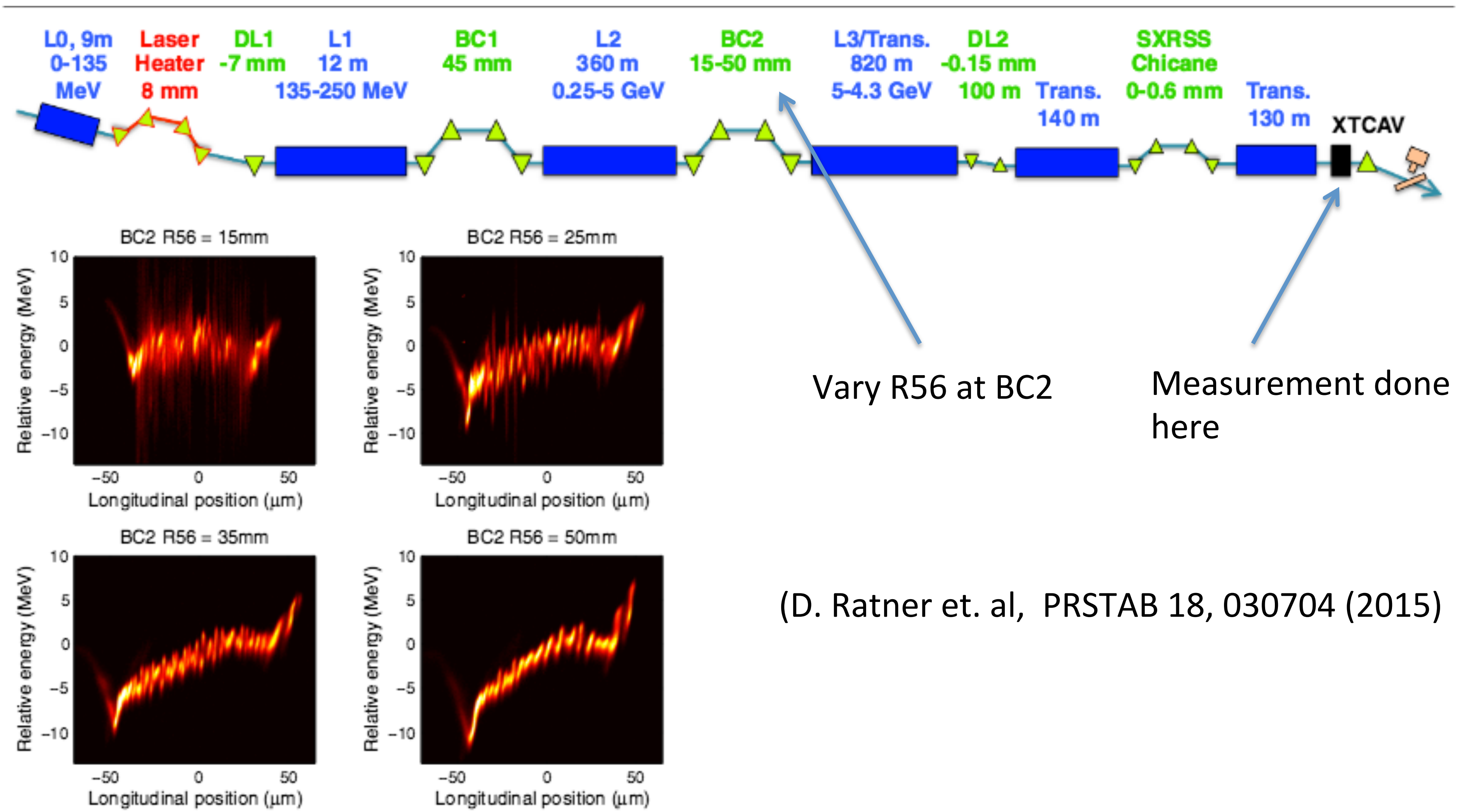


Z. Huang et al., PRST-AB 7 (2004)074401

Dominated by LSC since $Z_{LSC}(k) \propto k$

Venturini, PRSTAB 11, 030703 (2007)

MBI Measurement at LCLS



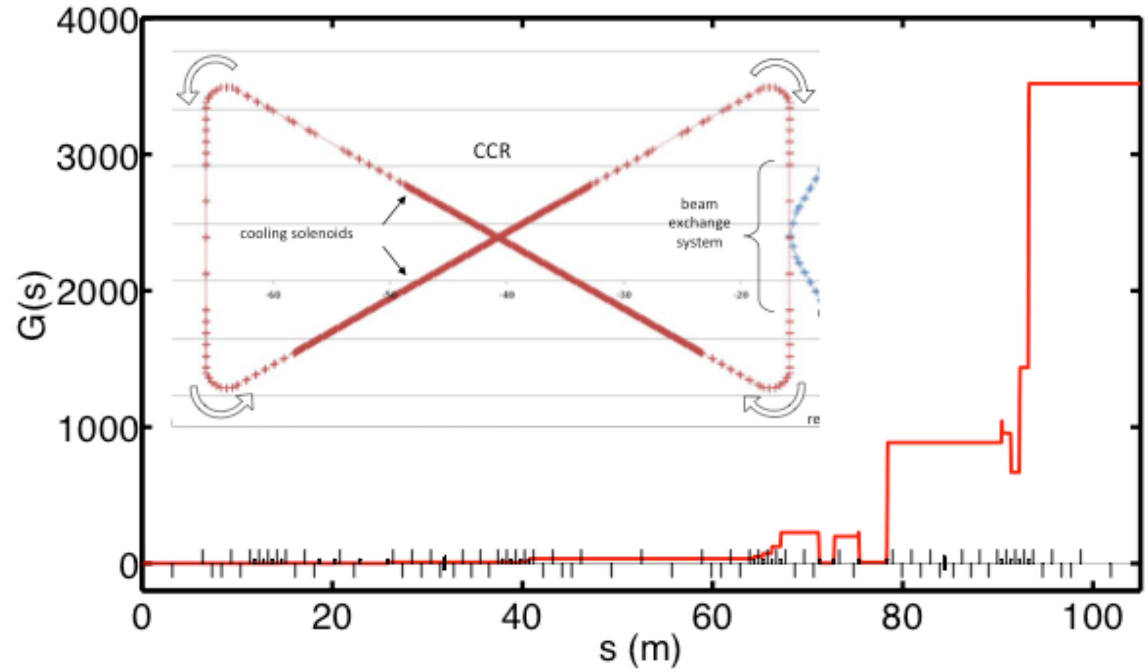
(D. Ratner et. al, PRSTAB 18, 030704 (2015)

MBI in the MEIC Circulator Cooler Ring

Beam Parameters

Name	Value	Unit
Beam energy	54	MeV
Bunch current	60	A
Norm. emittance	3 (in both planes)	µm
$\beta_{x0,y0}$	10.695/1.867	m
$\alpha_{x0,\ y0}$	0.0/0.0	
Slice energy spread	1×10^{-4}	
Chirp	0.0	m^{-1}

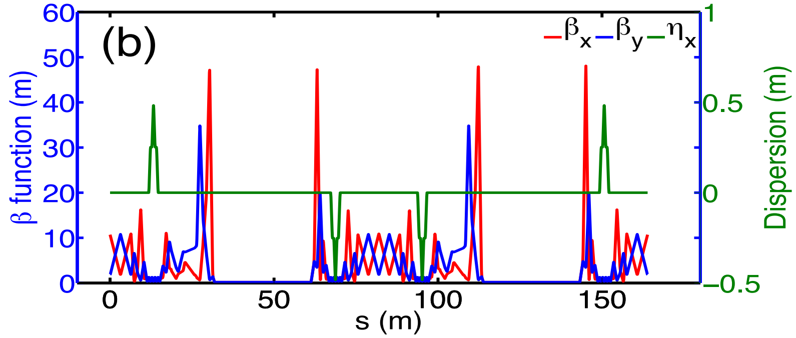
Microbunching Gain along the path length (1 turn)
(With steady-state CSR interaction only)

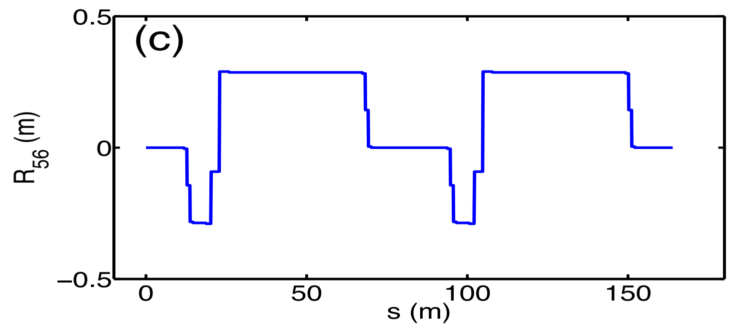


(C-Y Tsai *et al.*, see poster in this workshop)

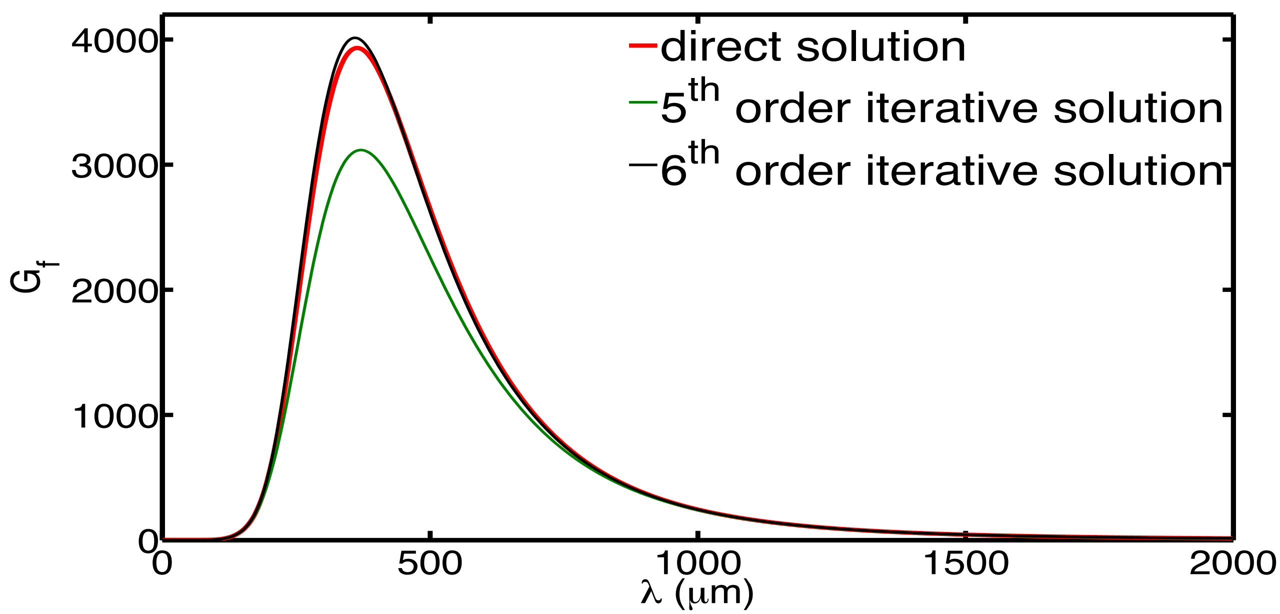
Microbunching Gain in CCR

- Lattice functions for CCR



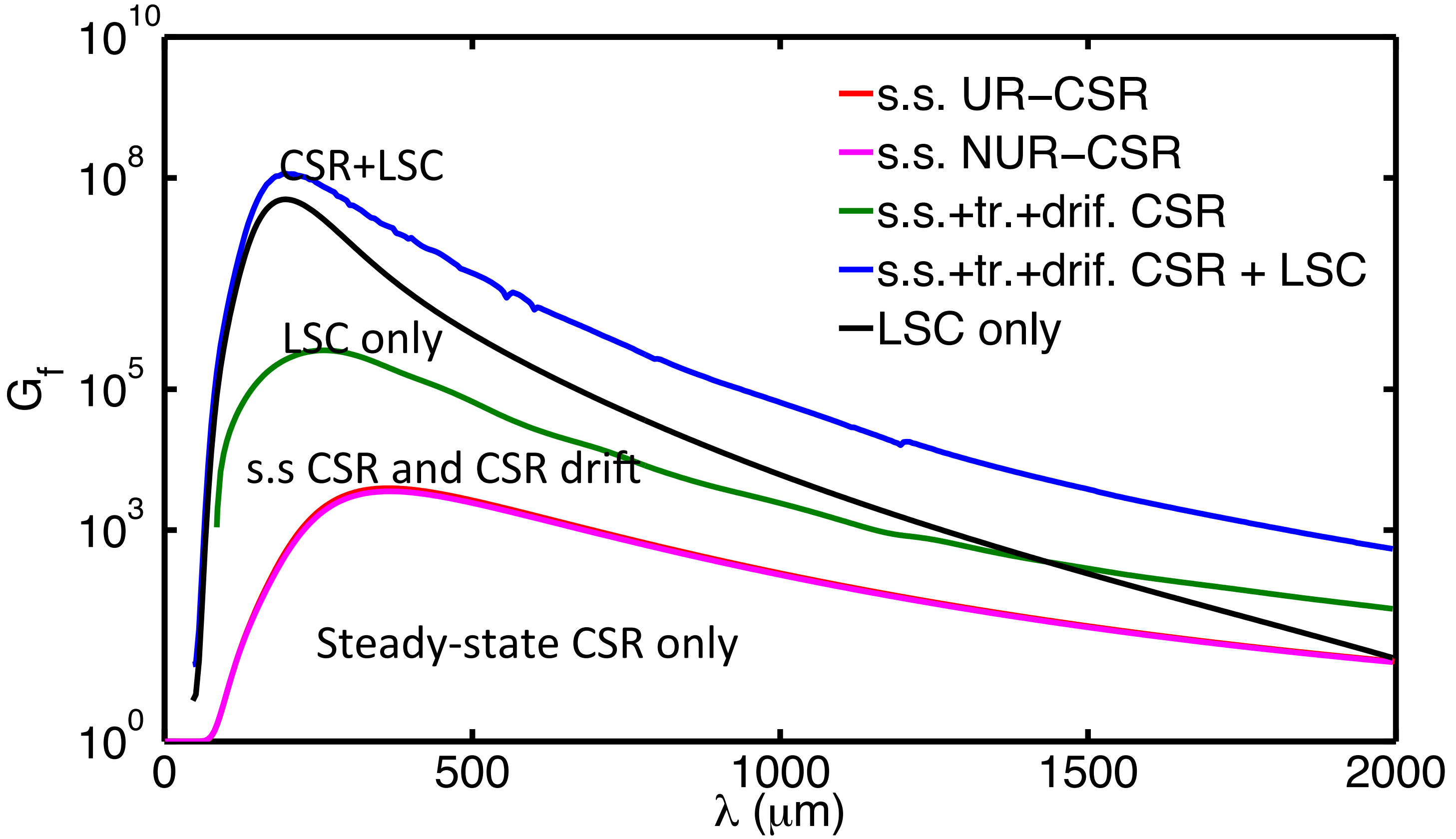


- Staged microbunching gain spectrum for one pass through CCR



Contributions from Various Impedances

- Microbunching gain spectrum for one pass through CCR



- This only gives the growth rate in the linear regime. The MBI will saturate quickly in the nonlinear regime.

IV. Mitigation Methods

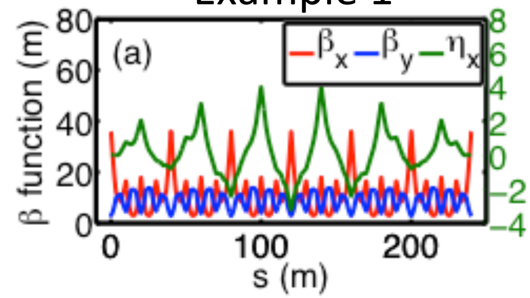
- Local isochronicity of optical lattice
  - Small R_{56}
  - Comparison of MBI for two different lattices
- Use magnetized beam
  - Larger transverse emittance for Landau damping
  - Possible shielding of CSR by vacuum pipe

➢ **Lattice Impact:** two 1.3 GeV high-energy recirculation arcs

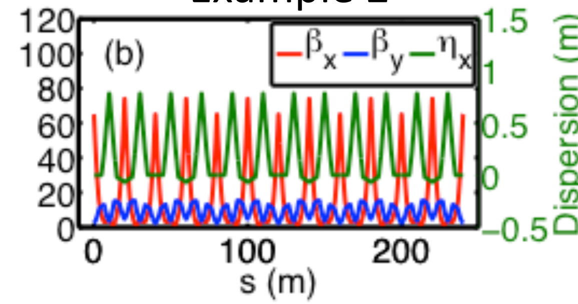
Name	Example 1 (large R_{56})	Example 2 (small R_{56})	Unit
Beam energy	1.3	1.3	GeV
Bunch current	65.5	65.5	A
Norm. emittance	0.3	0.3	µm
β_{x0}	35.81	65.0	m
α_{x0}	0	0	
Slice energy spread	1.23×10^{-5}	1.23×10^{-5}	

- Twiss parameters along the arc:

Example 1

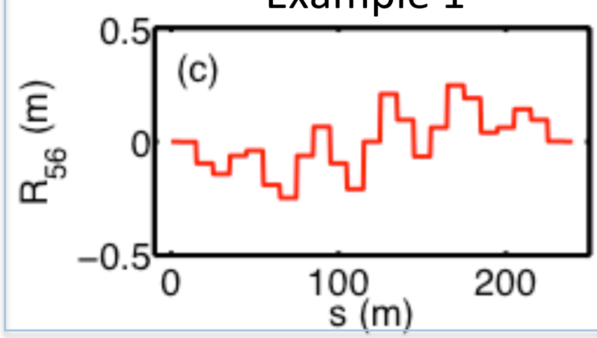


Example 2

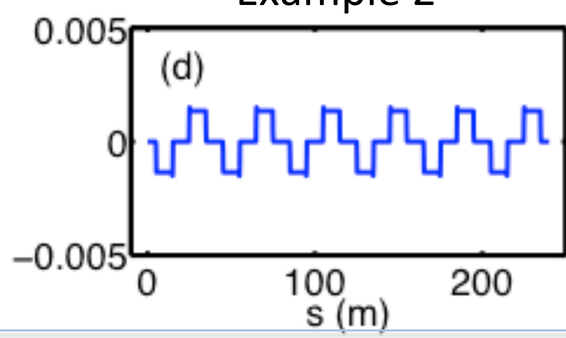


- Momentum compaction along the arc:

Example 1



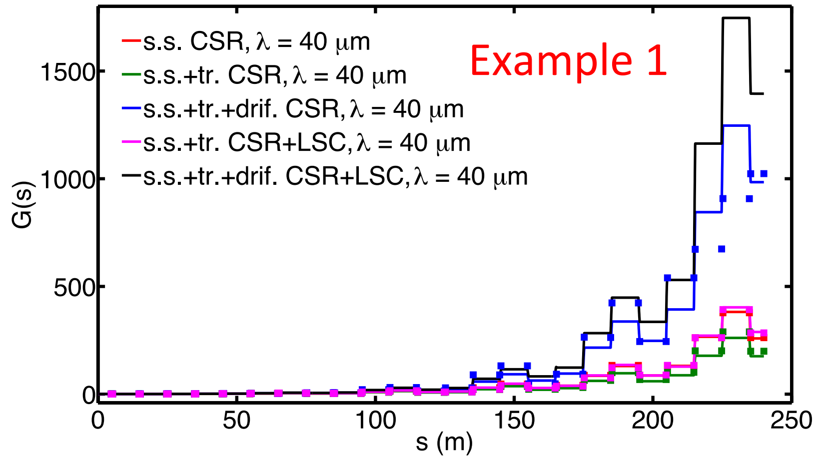
Example 2

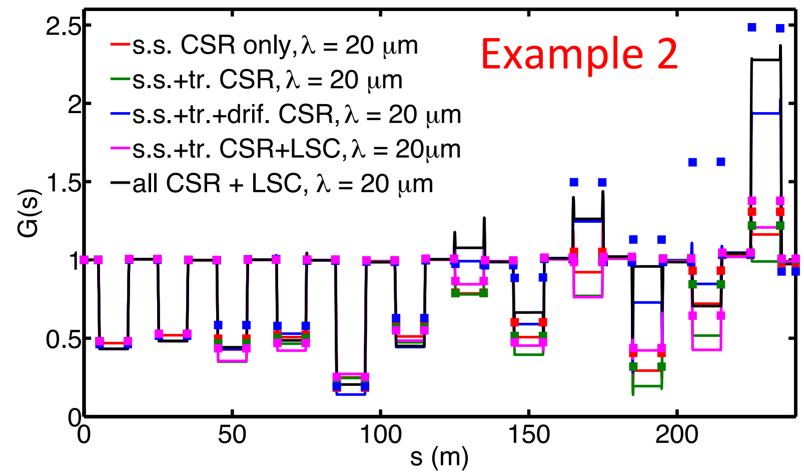


(D. Douglas *et al*, arXiv)

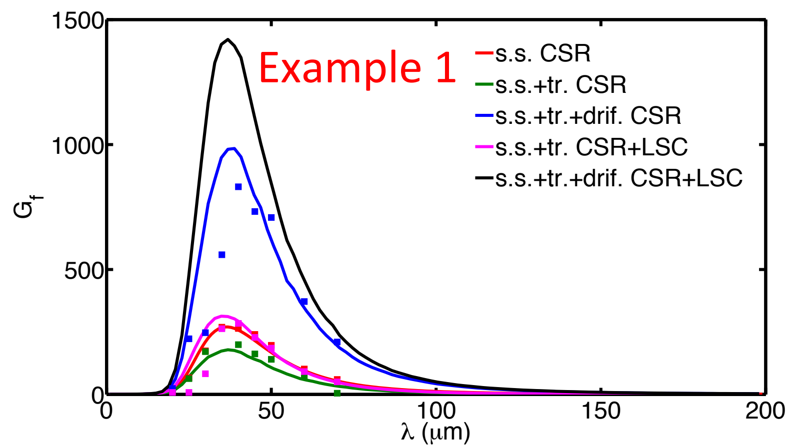
Microbunching Behavior for the Two Example Arcs

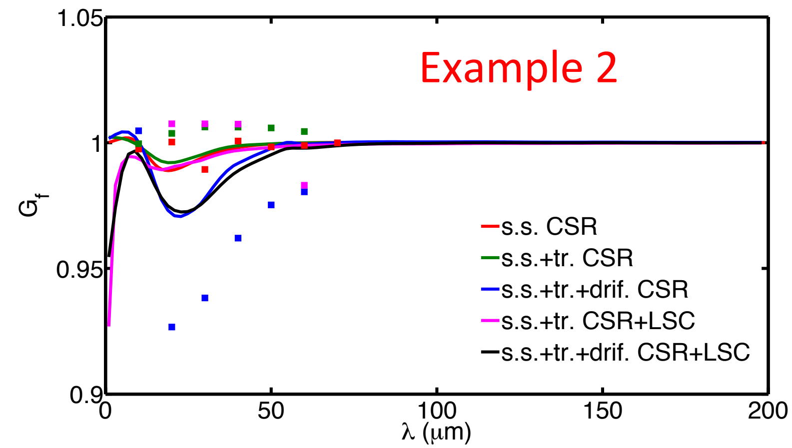
- Microbunching gain along the arc





- Microbunching gain spectrum at the end of the arc





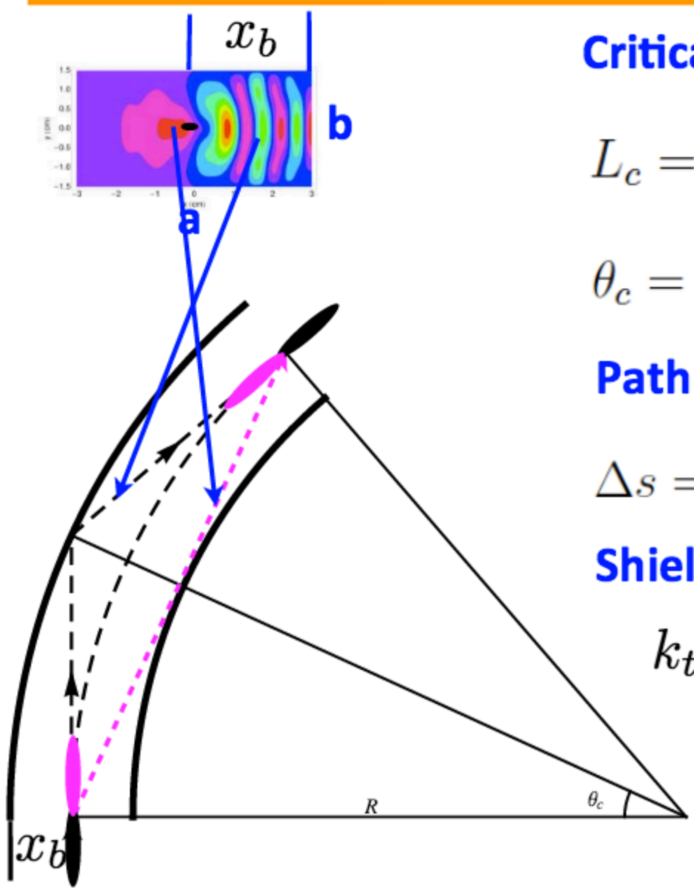
Magnetized Beam

- Transport the beam with angular momentum through dipole with focusing index ½---axial symmetric focusing in dipole
- Large emittance is likely to cause stronger Landau damping at short wavelength
- Push the peak of microbunching gain spectrum to larger wavelength
- MBI could be suppressed by shielding of CSR occurs at longer wavelength
- More complete theoretical and numerical study will be carried out

(suggested by Ya. Derbenev)

CSR Shielding by Vacuum Pipe

Outer-wall reflection can be well approximated by a geometric model [Derbenev (1995), Carr (2001), Sagan (2009), Oide (2010)]



Critical length (Catch-up distance):

$$L_c = 2R\theta_c \approx 2\sqrt{2Rx_b} \qquad x_b \ll R$$

$$\theta_c = \mathrm{ArcCos}\left(R/(R+x_b)\right) \approx \sqrt{2x_b/R}$$

Path difference:

$$\Delta s = 2R(\mathrm{Tan}(\theta_c) - \theta_c) \approx \frac{4}{3}\sqrt{\frac{2x_b^3}{R}}$$

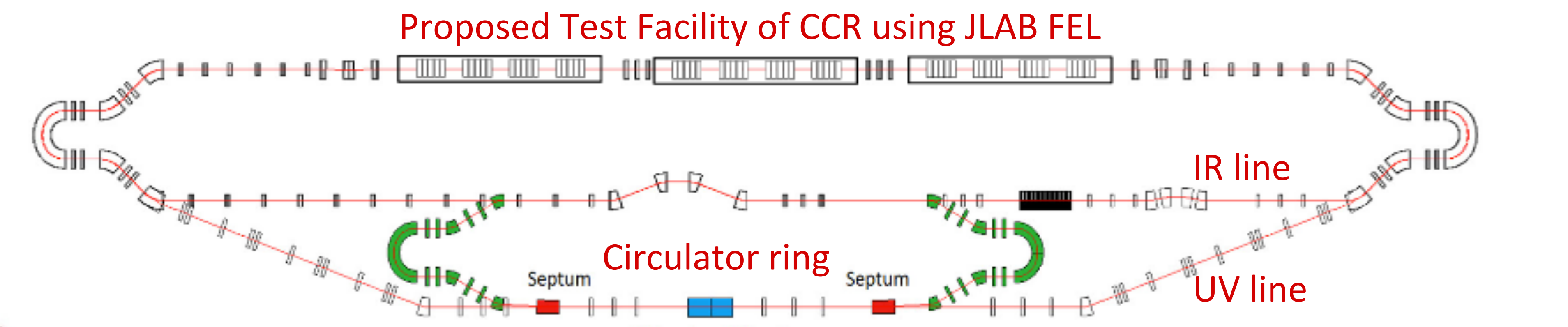
Shielding threshold:

$$k_{th} = \pi\sqrt{R/b^3}$$

Y. S. Derbenev, et al., TESLA FEL-Report 1995-05 (1995).
G. L. Carr, et al., PAC'01, p. 377 (2001).
D. Sagan, et al., PRST-AB 12, 040703 (2009).
K. Oide, Talk at CSR mini-workshop, Nov. 08, 2010.
D. Zhou, et al., Jpn. J. Appl. Phys. 51 (2012) 016401.

Experimental Test

- Demonstrate the capability of transporting high-brightness beam without degrading phase space quality
- Verify the theoretical and numerical predictions; test the codes



- To produce the same microbunching effects in the test facility as in the CCR, we need to prepare a bunch with
  - Comparable I_{peak}/γ
  - Comparable intrinsic spread $\varepsilon_x, \varepsilon_y, \sigma_p$

V. Conclusion

- CCR has a big potential to enable high-energy electron cooling by using electron source of achievable average current
- However, CSR and LSC induced microbunching instability could heat up the cooling beam during its transport in CCR
- Microwave physics is largely understood and Vlasov solver is developed for non-magnetized beam
- Theories and simulations are to be benchmarked with experiments, and theory could give guidance on the scaling for test facilities
- Further studies are planned for microwave physics of magnetized beam in CCR, and mitigation schemes will be explored to successfully transport magnetized beam through CCR for high energy cooling